Ice Sheet System Model

From Science to Software

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Outline

Introduction

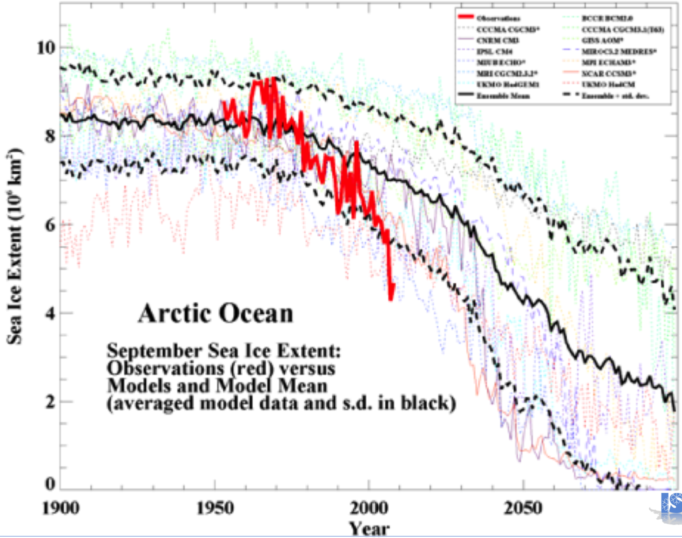
- Why ice sheet modeling at NASA/JPL?
  - → NASA missions (InSAR, ICESat, GRACE, EOS)
  - → NASA science mission to planet Earth to observe, understand and predict changes in the Earth system in response to human influence
- IPCC AR4 sea level rise in the 21st century excludes rapid changes from ice sheets

  "What's the use of having developed a science well enough to make predictions, if, in the end, all we're willing to do is stand around and wait for them to come true?" (Prof. Sherry Rowland, Nobel Prize in Chemistry 1995).

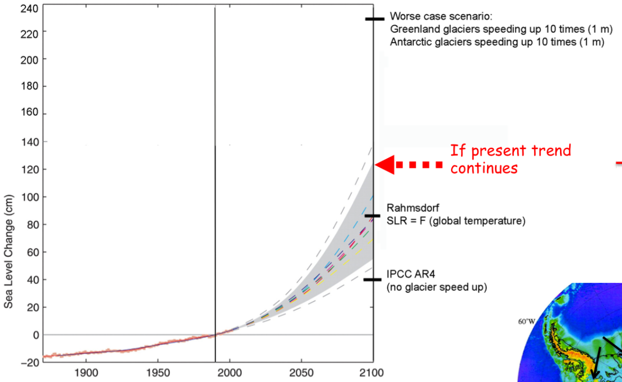
  Root cause of the failure of numerical models: lack of observations to evaluate their physical skills and time scales.

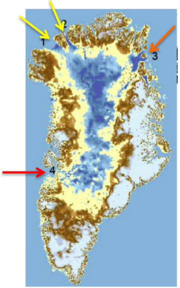
History

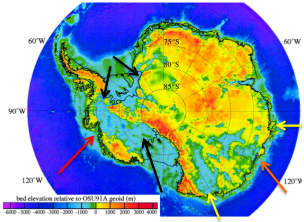
The case of sea ice



Sea-level in the 21st Century and beyond

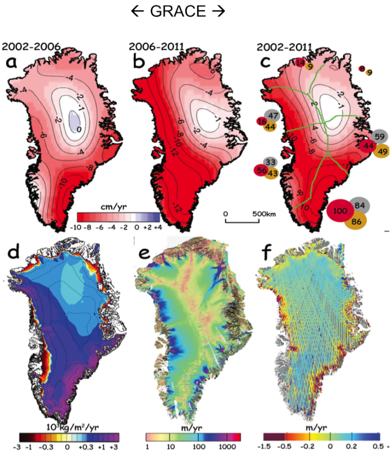






The most vulnerable sectors are marine based (blue color in right panels) and exposed to ocean heat.
Red arrow: fast retreat.
Orange arrow: initial changes. Yellow: at risk now

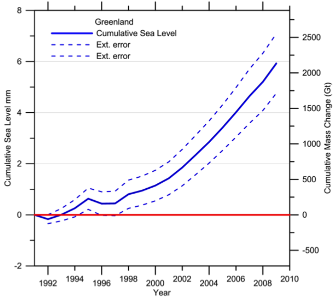
Greenland Ice Sheet mass loss increases with time



SMB

Height change

Velocity



- Upper panel: Summary estimate of contribution to sea level from 12 studies, 3 techniques (Alison and Rignot, in prep)
    - 50% loss from surface melt, 50% from glacier flow
- Left panel:

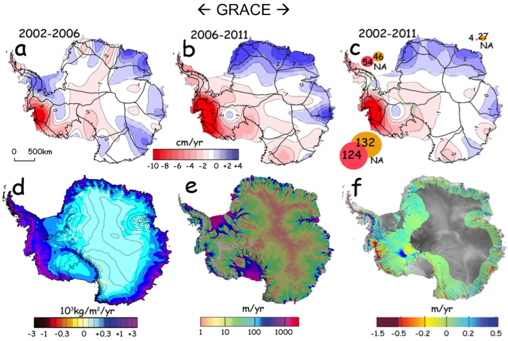
(a-c) Mass loss (in cm/yr water) from (Velicogna, 2009)

(d) SMB from RACMO for 1989-2004 (Ettema et al., 2009)

(e) Ice velocity from InSAR for 2007-2009 (Rignot and Mouginot, in prep)

(f) Changes in surface elevation from ICESat for 2003-2008 (Pritchard et al. 2008)

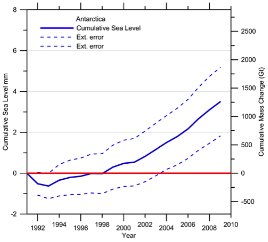
Antarctic Ice Sheet mass loss: comparable to Greenland's



SMB

Velocity

Height change



- Right panel: C Synthesis of 12 studies, 3 techniques, for Antarctica. Ice loss dominated by glacier flow
- Left panel: (a-c) Mass loss (in cm/yr water) from GRACE (Velicogna, 2009); (d) Surface mass balance from RACMO for 1989-2004 (Lenaerts et al., in press); (e) Ice velocity from InSAR for 2007-2009 (Rignot et al., 2011); and (f) changes in surface elevation from ICESat for 2003-2008 (Pritchard et al. 2008).

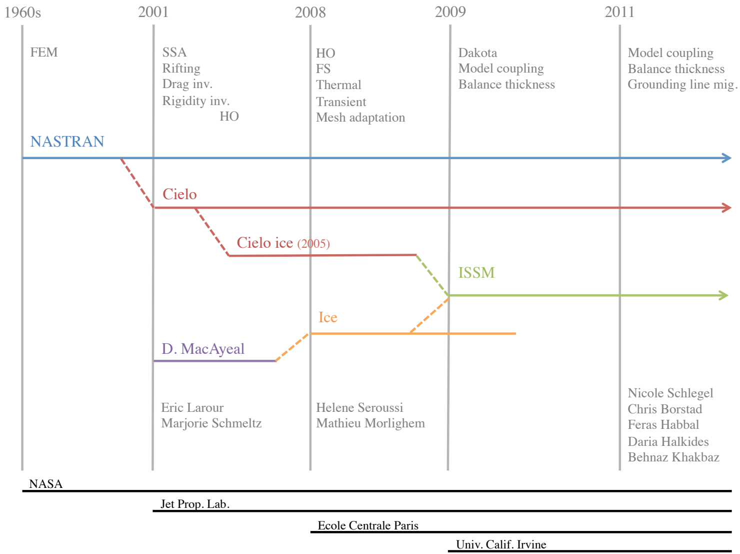
Root causes of ice sheet changes

- Surface mass balance: well understood.
- Glacier changes: understood to zeroth order or poorly.
- Example 1: enhanced basal lubrication not a major driver.
- Basal friction: not well understood, no evaluation of inverse methods.
- Bed geometry - critical to tide-water glacier or marine ice sheet instability
  - understood but not well observed nor modeled.
- Example 2: ice-ocean interactions always suspected to be important, but discovered to be dominant, and ocean forcing is not well known.
- Example 3: Nearly zero progress on a calving law.
- Example 4: Longitudinal transmission of stresses thought to be insignificant turn out to be dominant.
- Example 5: Thermal regime of ice sheets is largely unknown (geothermal flux, convection, in situ observations).

How to predict ice sheets?

- First challenge: demonstrate that numerical models are physically realistic.
- → Stokes equations
- → Right boundary conditions
- → Replicate observations, time scale, magnitude, geographic distribution, timing.
- Second is to get realistic forcing for projections
- More realistic goal is a sensitivity study of well-evaluated models.
- And perhaps be overly cautious about "predictions".

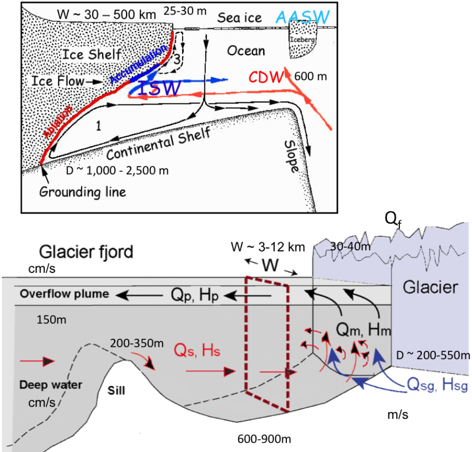
History of ISSM



Science Targets

- Surface mass balance is not a major impediment on predicting ice sheet evolution thanks to efforts like RACMO.
- Grounding line dynamics: Can ice sheet models make grounding line advance and retreat realistically, on the right time scale?
- Calving dynamics: How can we model calving, validate the modeling and determine the influence of calving instabilities on glacier flow.
- Ice-ocean interactions (next slide): ice shelf is well studied, calving face is new.
- Ice rheology: complex and non-uniform on ice shelves, not well known or evaluated on grounded ice.
- Basal friction: not observed, only deduced from inverse methods, but assumes a known rheology.
- How does basal friction relate to the subglacial hydrology? Slipperiness of sediments? Heat flow? Does it change with time?
- Other factors of importance: Softening of lateral shearing? Sikkusak? Cryo-hydrologic warming?

Ice-ocean interactions



Motyka et al. 2003

Rignot et al., NG 2010.

Ice Shelves (Antarctica):

- THC from sea ice formation or inflow of intermediate-depth warm water (CDW).
- Melting point increases with depth 0.75 $^{\circ}$C/km.
- Melt increases 10 m/yr/$^{\circ}$C.
- Melt rate $\sim$ 10 cm to 100 m/yr.
- Removes $\sim$50% of ice before calving.

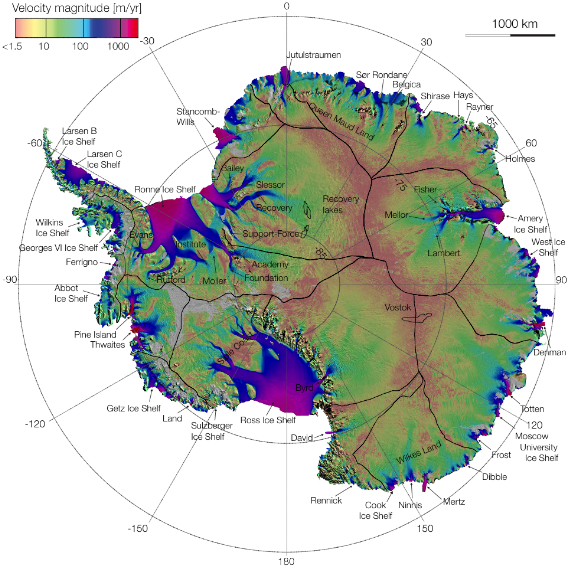
Tidewater Glaciers (Greenland):

- Forced convective flow driven by sub-glacial water discharge.
- Melt rate 10^1-10^2 $\times$ larger.
- Up to several meters/day.
- Removes $\sim$50% of ice before calving.
- Low in winter.

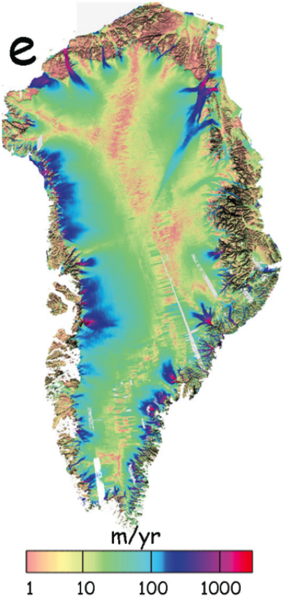
Observations: A game changer

- The game changer in ice sheet modeling is not computing power, or novelty in numerical analysis but in observations.
- Major observational additions on ice sheets since 1992 and especially 2003:
  - Ice sheet motion maps for Greenland and Antarctica.
  - BEDMAP 2, IceBridge (2016 and beyond), IceCap and others $\rightarrow$ thickness
  - ERS/Envisat altimetry, ICESat-1, IceBridge, Cryosat $\rightarrow$ height changes
  - GRACE, GRACE follow-on $\rightarrow$ mass changes
  - ERS1-2, Envisat ASAR, RADARSAT-1, -2, ALOS PALSAR and future missions: Sentinel-1, RADARSAT-3, PALSAR-2, DESDynI-R $\rightarrow$ velocity and changes.
- Observational gaps of potential serious impact:
  - Melt rates of submerged parts of the ice sheets, especially TWG.
  - Geothermal flux.
  - Basal friction.
  - Ice shelf rifting or calving or submarine crevassing.
  - Thickness maps compatible with objectives of numerical models

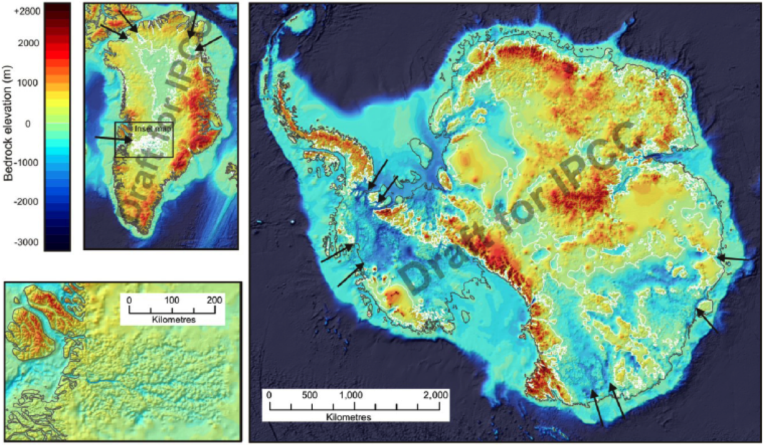
Antarctica


Velocity magnitude [m/yr]
<1.5
10
100
1000
1000 km
0
30
60
90
120
150
180
-30
-60
-90
-120
-150
-65
-75
-85
Jutulstraumen
Sør Rondane
Belgica
Shirase
Hays
Rayner
Holmes
Fisher
Mellor
Amery
Ice Shelf
West Ice
Shelf
Lambert
Vostok
Denman
Totten
Moscow
University
Ice Shelf
Frost
Dibble
Mertz
Ninnis
Cook
Ice Shelf
Rennick
Wilkes Land
David
Ross Ice Shelf
Byrd
Siple Coast
Sulzberger
Ice Shelf
Land
Getz Ice Shelf
Pine Island
Thwaites
Abbot
Ice Shelf
Ferrigno
Georges VI Ice Shelf
Wilkins
Ice Shelf
Larsen B
Ice Shelf
Larsen C
Ice Shelf
Ronne Ice Shelf
Stancomb-
Wills
Bailey
Slessor
Recovery
Recovery
lakes
Queen Maud Land
Support-Force
Evans
Institute
Academy
Foundation
Rutford
Moller

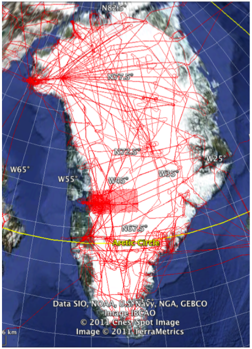
Greenland

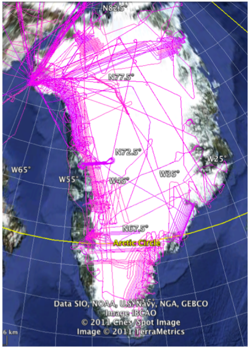


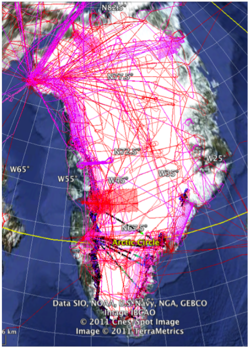
BEDMAP-2


Bedrock elevation (m)
+2800
2000
1000
0
-1000
-2000
-3000
Inset map
Draft for IPCC
0
100
200
Kilometres
0
500
1,000
2,000
Kilometres
Draft for IPCC

IceBridge 2009-present



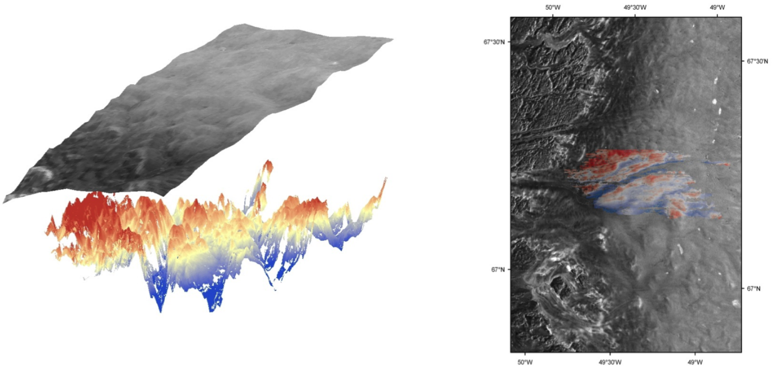




1993-2008

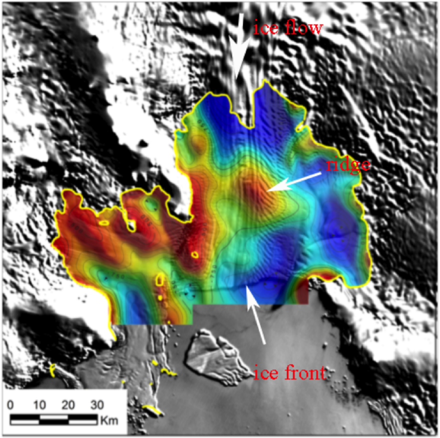
2009-2011

IceBridge



Tomographically derived surface and basal topography (left) for Russell Glacier (right). Ice thickness is about 1000 m. (Courtesy of X. Wu and J. Paden).

Ice shelf bathymetry

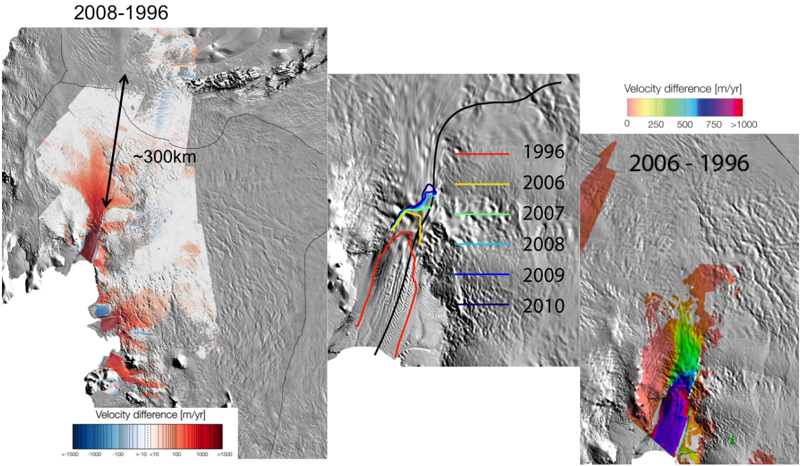


Sea floor topography beneath the floating ice shelf in front of Pine Island Glacier, West Antarctica unveiled by the NASA-Icebridge mission in Nov. 2009 using airborne gravity and showing a previously unknown sub-ice-shelf ridge at 76°S, 104°W that may have anchored the glacier 5-6 decades ago. Bed elevation color coded from blue (deep) to red (high) overlaid on a MODIS mosaic of Antarctica (Courtesy M. Studinger, NASA GSFC, 2010).

ISSM

Larour et al.

Amundsen Sea: 1996-2010

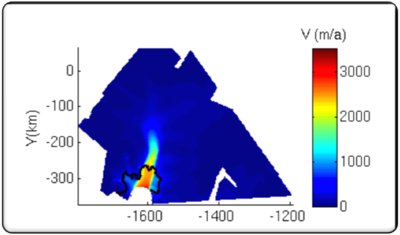


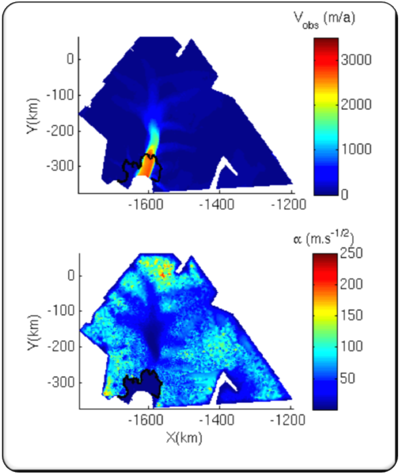
Engineering drivers

Inverse methods

Infer unknown parameters (basal friction, ice rigidity) using an ice flow model to best-fit InSAR surface velocities:

$$J = \iint_{\text{Surface}} \frac{1}{2}\left[(u-u_{\text{obs}})^2+(v-v_{\text{obs}})^2\right]dxdy$$

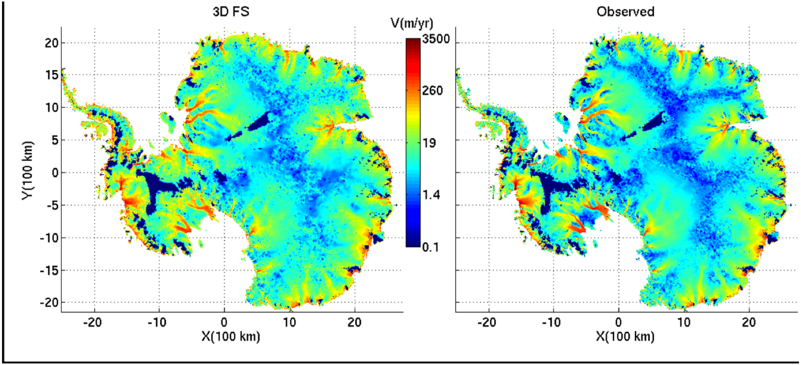




Engineering drivers

High resolution, large scale simulations

Model whole continental ice sheets at high resolution (1 km horizontal, 10–20 layers vertically)

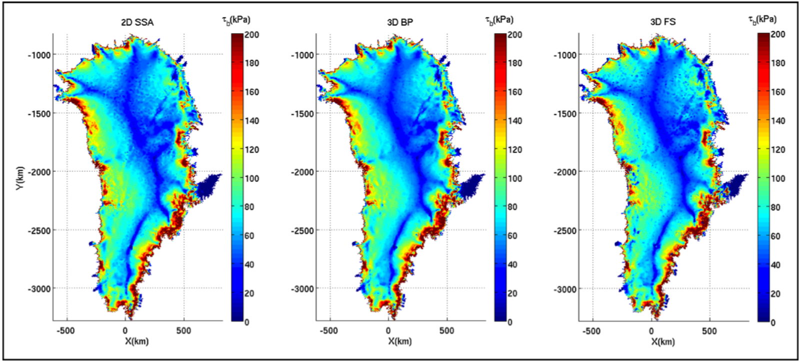


ISSM

Larour et al.

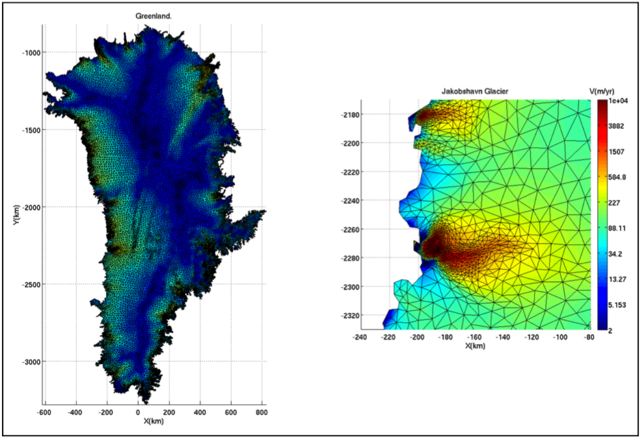
Engineering drivers

Higher-order modeling



Technology
Finite Element Method

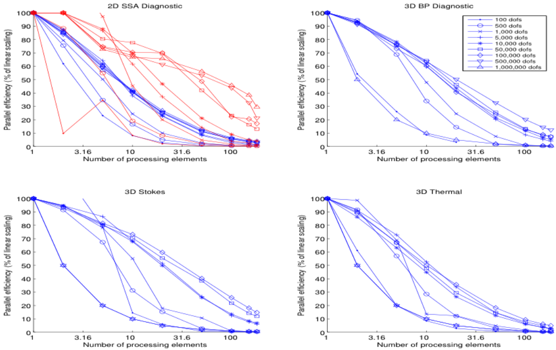
The Finite Element Method (FEM) seamlessly integrates fully unstructured meshes, multi-physics and anisotropic adaptivity.



Technology

Parallel computing

- ISSM was designed as a parallel architecture with serial capabilities, instead of the opposite. The goal is to make parallel computing as easy as possible.
- ISSM relies on PETSc and MPICH to run on any type of parallel platform, be it shared or distributed clusters, as well as multi-core desktops.
- Scaling is good for the entire architecture, with extensive work being carried out to apply efficient parallel iterative solvers.



Technology

MATLAB

- ISSM is hosted in MATLAB, a widely-used multi-purpose platform
  - ISSM is encapsulated within mex modules (MATLAB routines)
  - Pre and post-processing done in MATLAB
  - Serial runs carried out within MATLAB
  - MATLAB layer can be removed to compile a parallel executable for parallel computations
  - For computationally challenging processing routines, multi-threading seamlessly integrated within ISSM
- Example of pre-processing of thickness dataset:

```
>> disp('      reading thickness and bedrock');
>> load(thickness);
>> md.geometry.thickness=InterpFromMeshToMesh2d(index,x,y,thickness,md.mesh.x,md.mesh.y);
>> md.geometry.bed=InterpFromMeshToMesh2d(index,x,y,bed,md.mesh.x,md.mesh.y);
```

Technology

Multi-physics

- ISSM is entirely written in C++ and is therefore object-oriented. This allows for ice flow modeling formulations to be deeply integrated within the software. Every type of ice flow model is encapsulated in low-level routines which can be called by general drivers.
- Example: creation of a stiffness matrix:

```
for(i=0;i< elements->Size();i++){
element=elements->GetObjectById(i);
element->CreateKMatrix();
}
```

element is a derived object from a Tria or Penta class.

- Multi-physics and coupling between different types of formulations is transparent to the user, provided low-level routines are implemented.
- Code is structured to assimilate new models with minimal impact, as only additional low level routines are required.

Thanks!

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